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Correlation of geomagnetic anomalies recorded at Muntele Rosu Seismic Observatory (Romania) with earthquake occurrence and solar magnetic storms

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ABSTRACT

The study presents a statistical cross-correlation between geomagnetic anomalies, earthquake occurrence and solar magnetic storms. The working data are from: (i) geomagnetic field records from Muntele Rosu (MLR) Observatory, and from Surlari (SUA) and/or Tihany (THY) INTERMAGNET Observatories; (ii) seismic data for the Vrancea source zone; and (iii) daily geomagnetic indices from the NOAA/Space Weather Prediction Center. All of the geomagnetic datasets were recorded from 1996 to the present, at MLR, SUA or THY, and they were automatically corrected using a LabVIEW program developed especially for this purpose, highlighting the missing or bad data. Missing data blocks were completed with the last good measured value. After correction of the data, there were a number of issues seen regarding previous interpretations of the geomagnetic anomalies. Some geomagnetic anomalies identified as precursory signals were found to be induced either by increased solar activity or by malfunction of the data acquisition system, which produced inconsistent data, with numerous gaps. The MLR geomagnetic data are compared with the data recorded at SUA/THY and correlated with seismicity and solar activity. These 15 years of investigations cover more than a complete solar cycle, during which time the solar-terrestrial perturbations have fluctuated from very low to very high values, providing the ideal medium to investigate the correlations between the geomagnetic field perturbations, the earthquakes and the solar activity. The largest intermediate depth earthquake produced in this interval had a moment magnitude Mw 6.0 (2004) and provided the opportunity to investigate possible connections between local geomagnetic field behavior and local intermediate seismicity.

1. Introduction

Large networks of ground-based instruments [Yumoto et al. 1995, 1996, 2001, Yumoto 2004; e.g. the International Real-Time Magnetic Observatory Network, INTERMAGNET], and even some satellite-based systems [Lagoutte et al. 2006, Parrot et al. 2006], have been dedicated to the monitoring of the geomagnetic field over the last two decades. Several studies have reported the identification of possible anomalous magnetic signals prior to earthquake occurrences [Hayakawa and Fujinawa 1994, Stanica et al. 2006, Stanica and Stanica 2007, 2009, Moldovan et al. 2009, Yumoto et al. 2009, Takla et al. 2011], or increased numbers of seismic events after or during magnetic storms [Hayakawa et al. 2002, Kessel et al. 2006].

Anomalous changes in the geomagnetic field can occur before and during seismic events. As the lithosphere deforms, rock properties can change in response to changes in stress piezomagnetism or to changes in the distribution and composition of fluids in the crust [Freund et al. 1999, Pulinets and Boyarchuck 2004]. The reported expected changes are in the range of a few nT. The problem of identification of seismo-magnetic effects in geomagnetic time series is complicated by the presence of disturbances, which are mainly due to irregular transient time variations that are generated in the terrestrial ionosphere and magnetosphere, and which also depend on the geological structure of the area.

The purpose of this study is to examine the dynamics of geomagnetic field variations in relation to the Vrancea (Romania) crustal and intermediate seismic activity and to magnetic storms.

The Vrancea seismogenic zone is situated at a bend in the eastern Carpathians, and it is bounded to the northeast by the East European Platform, to the south by the Moesian Platform, and to the west by the Transylvanian Basin. The crustal activity located in the depth interval of 10 km to 40 km is weak, with *Mw* <5.9 (3.4 in the study period) and an activity rate of 0.514526 for *Mw* >3.0 [Moldovan et al. 2008]. The intermediate depth seismic zone (60 km to 200 km) is concentrated within a very small area, which is 80 km long and 40 km wide. The activity rate is 1.762380 for $Mw > 5.0$, with about three strong events ($Mw \geq 7.0$) per century. The largest known earthquake had a moment magnitude *Mw* 7.7.

The largest intermediate depth earthquake that occurred in Vrancea in the study time interval had the moment magnitude *Mw* 6.0 (on October 27, 2004) [Moldovan et al. 2009]. This provided the opportunity to investigate possible connections between the geomagnetic field behavior and the local intermediate depth seismicity. The most significant geomagnetic anomaly was recorded at the Muntele Rosu (MLR) Observatory in February-March, 2010, but was only followed by an *Mw* 3.8 intermediate earthquake.

As the largest moment magnitude of the crustal events that occurred in Vrancea in the study period was *Mw* 3.4 (only 36 events with $Mw > 3.0$, with three of these with *Mw* 3.4 during the last 15 years: July 1, 2000, September 6, 2008, and April 28, 2009), we could not investigate any reliable correlation between the geomagnetic field behavior and the crustal earthquake occurrence. Even if earthquakes with $Mw < 3.4$ are crustal, they are not of sufficient strength to produce discernible changes in the geomagnetic field variations.

For more than 10 years, the geomagnetic field was monitored in Romania at only one location, which is situated at the edge of the Vrancea seismogenic zone, the MLR Observatory, and which has been related to crustal and intermediate depth seismicity. The MLR location was picked in such a way as to ensure the optimum positioning with respect to the Vrancea seismic area (Figure 1). Moreover, this site was chosen so as to be distant from railroads and any other sources of noise, to avoid disturbing signals. This electromagnetic observatory consists of:

(i) a three-axis magnetic field sensor (Fluxgate; +/–70 μT measuring range; Bartington Instruments, UK);

(ii) a data-logger acquisition module (six channels, 24-bit resolution, programmable sample rate; Bartington Instruments);

(iii) a computer for data storage and preliminary processing.

The three-axis magnetic field sensor is a low-noise type, which provides superior characteristics; namely, a band larger than 2 kHz, which is actually up to 3 kHz; 15 pT rms/(Hz^1/2) noise, and a lower-than-standard phase error. The parameters of the data-logger acquisition module are controlled by a software program with a sample rate of 0.2 samples per second and which displays the average values every 60 s. The magnetic equipment was placed in a specially designed, vibration-proof, nonmagnetic, thermostatic tunnel.

During the first stages of its functioning (1998-2006), a manual system was used for both the data transfer and processing. Special programs were created over the last 5 years [Moldovan et al. 2010] to automate these processes and for correcting the already recorded data. This provided an opportunity to reconsider some of the conclusions from

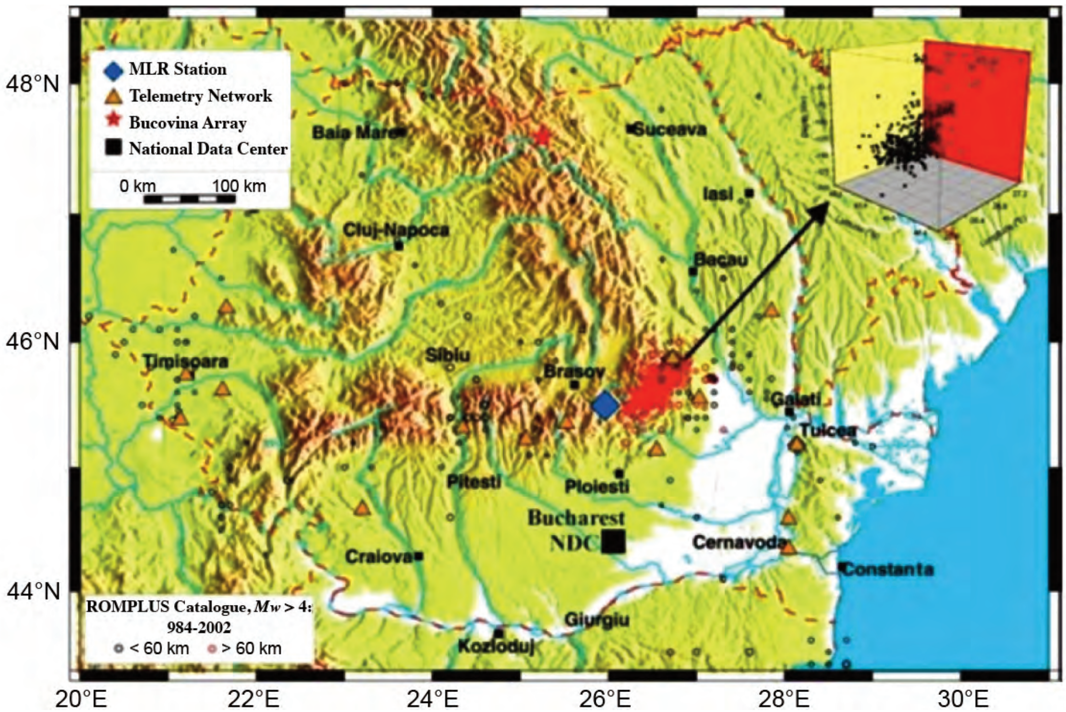


Figure 1. Distribution of the epicenters and hypocenters of the Vrancea (Romania) earthquakes. Blue diamond, the geomagnetic MLR Observatory; black square, the National Data Center from Bucharest; red dots, the Vrancea earthquakes.

previous studies [Enescu et al. 1998, 1999a,b, 2001) that had incorrectly classified all geomagnetic variations as seismo-magnetic anomalies related to the occurrence of crustal and intermediate depth Vrancea earthquakes. Indeed, some of these were due to missing data or to solar storms.

The main difficulty in achieving an automatic supervision system for zones characterized by high seismic risk consists both in the monitoring of the values for representative parameters over long enough periods, and in the analyzing of their earthquake-preceding values to identify changes, and to calibrate the reading scale according to these changes and to the magnitudes of seismic events.

It is important to note here that using one geophysical parameter (the geomagnetic field in our case) is not sufficient to obtain a reliable earthquake forecasting method. Only by accumulating data obtained by means of more and more complex monitoring of the environment [Gheorghita et al. 2010], as well as by using an adequate analysis method, can this lead to improvements in earthquake prediction activities and to more efficient civilian protection.

2. The data

The present study used the following working data:

(i) The seismic data for the Vrancea source zone, taken from the seismic bulletins of the National Institute for Earth Physics;

(ii) The geomagnetic field records (1996-present) made at MLR National Institute for Earth Physics Observatory, and at the Surlari (SUA) and Tihany (THY) INTERMAGNET Observatories (see Table 1);

(iii) The daily geomagnetic indices, *Kp*, from the National Oceanic and Atmospheric Administration (NOAA)/ Space Weather Prediction Center.

To discriminate between local (tectonic) and global (solar) phenomena, the geomagnetic data from MLR observatory are compared with the data recorded at the SUA and THY geomagnetic reference stations, which are located outside the epicentral region. These recordings were provided through the INTERMAGNET Project. The geomagnetic data were also correlated with the global geomagnetic indices, *Kp*, which are represented as the sums of the 3-h *Kp* values for single days (ΣKp).

Code of the Magnetic Observatory	Latitude (°N)	Longitude (°E)	Altitude (m asl)
MLR	45.49	25.95	1,360
SUA (INTERMAGNET)	44.68	26.12	84
THY (INTERMAGNET)	43.10	17.54	187

Table 1. The locations of the magnetic observatories used in the correlation study.

3. Data corrections

In this section, we emphasize and discuss some misinterpretations that were included in the study of Enescu et al. [1998], where missing data blocks within datasets and solar storms with geomagnetic signatures were interpreted as anomalous variations in the geomagnetic field, and were consequently falsely identified as seismo-magnetic anomalies. This point of the study is necessary, because the cited studies gave unrealistic correlations between geomagnetic anomalies and earthquake occurrence. These apparent correlations provided a success rate for earthquake prediction through geomagnetic anomalies of about 92%, which is far from a realistic statistic, especially for intermediate earthquakes with magnitudes that do not exceed *Mw* 5.5.

The first source of false magnetic anomalies identified prior to an earthquake occurrence was a bad and inconsistent dataset that was affected by many gaps, some of which lasted for whole days. These gaps introduced leaps in the data that can be interpreted as precursory anomalies. This situation occurred because until 2006 the data recording and processing were conducted manually, and were not corrected for missing data. This stimulated us to develop a LabVIEW program that automatically corrects the datasets, highlighting the missing or bad data. Using this program, we reprocessed all of the recordings, and all of the datasets were automatically corrected by completing the missing data blocks with the last good existing values. The variations in the sum of the geomagnetic indices *Kp* (ΣKp) were also represented together with the time-variation diagrams of the geomagnetic components (X, Y, *Z*) at MLR Observatory.

The second source of interpretation errors were variations induced by solar storms that were identified by Enescu et al. [1998, 1999ab, 2001] as anomalous variations and were then falsely characterized as seismo-magnetic precursors. Until 2004 [Enescu et al. 2004], the geomagnetic data did not correlated with solar activity or weather conditions, which can strongly affect the data measured. The correlation of the recordings from MLR Observatory with the recordings from SUA or THY Observatories and the *Kp* indices show that many so-called seismo-magnetic anomalies that were previously identified were only normal influences of solar storms on the geomagnetic field.

Table 2 provides the parameters of the Vrancea earthquakes with magnitudes $Mw \geq 3.5$ that occurred in the period of 1997 to 1998 and that were correlated with the geomagnetic field by Enescu et al. [1998]. These data are reprinted from the Romanian Earthquake Catalogue [see Oncescu et al. 1998, updated], which is compiled by the Seismological Department of the Romanian National Institute of Earth Physics. Table 2 shows the time and date when these earthquakes occurred, the geographical coordinates of the epicenters (latitude, °N; longitude, °E), the

No.	Date (dd.mm.yyyy)	Hour	Lat. (°N)	Long. (°E)	Depth (km)	*Mw*	Magnetic components affected by precursory anomalies	*tpB* (after [1])	*qB* (after [1])	Date of anomaly (after [1])	*ΣKp* for 1 day	Start/finish date of revised anomaly	Shape of revised anomaly
1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	01.01.1997	1:44	45.7	26.6	141	4.9	BX , BY , BZ	7	v.g.	25.12.1996	-	-	No recorded anomaly – there were 5 days of missing data
2	18.12.1997	23:21	45.5	26.3	134	4.1	BX , BY , BZ	7-8	g	10-11.12.1997	22/20	-	No recorded anomaly – there were 6 days of missing data
3	14.01.1998	5:02	45.7	26.6	145	4.0	– BY , BZ	5	v.g	9.01.1998	15	9.01.1998/ 14.01.1998 (By)	By V-shaped/Bz step-type
4	19.01.1998	0:54	45.6	26.7	105	4.0	– BY , BZ	9	v.g.	9.01.1998	15	-“-	-“-
5	31.01.1998	21:14	45.5	26.3	136	3.6	– BY , BZ	21	v.g.	9.01.1998	15	22.01.1998/ 28.02.1998 (By)	By V-shaped – Earthquake possibly triggered by a $Kp = 19$ magnetic storm on 30.01.1998
6	19.02.1998	14:35	45.7	26.7	132	3.7	BX , BY , BZ	1	v.g.	18.02.1998	25	-	No recorded anomaly – there were 3 days of missing data – Earthquake possibly triggered by a $Kp = 25$ magnetic storm on 18.02.1998
7	28.02.1998	8:37	45.4	26.2	139	3.6	BX , BY , BZ	9–10	vg.	18.02.1998	25	-	No recorded anomaly – there were 3 days of missing data
8	06.03.1998	20:28	45.6	26.4	151	3.7	BX –	3	uns.	03.03.1998	20	-	No anomaly
9	13.03.1998	13:14	45.6	26.4	155	4.7	BX , BY , BZ	3-4	g.	10.03.1998	26	-	No visible anomaly. Earthquake possibly triggered by a $Kp = 26$ magnetic storm on 11.03.1998
10	09.04.1998	10:25	45.4	26.4	133	3.8	BX , BY –	7	s	2.04.1998	<15	12.03.1998/ 9.04.1998 (By)	By V-shaped – the earthquake occurred exactly at the end of the anomaly, during a small $Kp = 15$ magnetic storm
11	14.04.1998	1:03	45.7	26.6	147	3.8	BX , BY –	12	s	2.04.1998	<15	-“-	-“-
12	23.04.1998	6:37	45.8	26.7	90	3.8	BX – BZ	5	g	18.04.1998	20	18.04.1998 (By and Bz)	By and Bz step-type – Earthquake possibly triggered by a $Kp = 25$ magnetic storm on 23/27.04.1998
13	27.04.1998	9:31	45.7	26.5	155	3.7	BX – BZ	9	s	18.04.1998	20	18.04.1998	By and Bz step-type – Earthquake possibly triggered by a $Kp = 25$ magnetic storm on 23/27.04.1998
14	04.05.1998	16:10	45.7	26.5	139	4.0	BX , BY , BZ	2	v.g.	2/3/4.05.1998	36/35/38	-	Magnetic storm and not a precursory anomaly Earthquake possibly triggered by a $Kp > 35$ magnetic storm on 2/5.05.1998
15	02.06.1998	4:49	45.6	26.5	110	3.7	BX –	3-4	s	29/30.05.1998	24/23	-	No recorded anomaly- there were 2 days of missing data; The earthquake occurred 4 days after a $Kp = 24/23$ magnetic storm on 29/30.05.1998 with a possible triggering efect
16	03.07.1998	6:14	45.7	26.8	133	4.2	BX , BY , BZ	8	v.g.	25.06.1998	18	25.06.1998	Bx, By and Bz step-type changes. The anomaly was recorded during a magnetic storm that occurred on 24/25/26.06.1998 with $Kp = = 21/18/29$
17	27.07.1998	15:02	45.7	26.5	132	4.4	BX , BY , BZ	4	s	23/24.07.1998	29/25	-	No visible anomaly The earthquake occurred 4 days after a Kp = 29/25 magnetic storm on 23/24.07.1998 with a possible triggering effect
18	24.08.1998	23:27	45.6	26.5	152	4.0	BX , BY , BZ	4	v.g.	20.08.1998	22	20.08.1998	Bx, By and Bz step-type changes. The anomaly was recorded during a magnetic storm that occurred on 24/25/26.06.1998 with $Kp = = 21/18/29$
19	03.09.1998	13:42	46.8	26.4	25	3.7	BX , BY , BZ	5–6	v.g.	26/27/28/29/30.08.1998	29/42/29/18/20	-	No visible precursory anomalies; days of magnetic storms

[1] = [Enescu et al. 1998]; v.g. = very good; g = good; s = satisfactory; uns. = unsatisfactory.

Table 2. Seismological parameters and electromagnetic precursory data of all of the Vrancea earthquakes of magnitudes $Mw \geq 3.5$ that occurred in the period investigated by Enescu et al. [1998].

depths, *h*, of their hypocenters, and the magnitudes, *Mw*. The components of the geomagnetic field (*B*), which manifest precursor perturbations, are also given in Table 2 for each earthquake, as they were interpreted by Enescu et al. [1998]. The approximate values of the precursor time, *tpB*, were taken from the study of Enescu et al. [1998], and Table 2 includes our assessments of the quality, *qB*, of the precursor perturbations, which are of course of a subjective nature. The precursor times were measured from the onset of a magnetic anomaly to the moment at which an earthquake occurred.

Enescu et al. [1998] showed that significant magnetic anomalies (perturbations) appeared prior to earthquakes of magnitudes *Mw* >3.5 during their period of study from 1996 to 1998. As indicated in Table 2 (columns 7-10), and as stated by Enescu et al. [1998], for 10 out of a total of 19 earthquakes of *Mw* >3.5 that occurred in their study period, all three of the magnetic components were disturbed by anomalies; in seven of the other earthquakes, only two components were affected, while in the last two of the earthquakes (of threshold or close-to-threshold magnitude, *Mw* 3.5), anomalies were found in only one component, and even these were doubtful. It is important to note that precursor anomalies were very evidently highlighted even before the crustal earthquake of *Mw* 3.1 that occurred within the period of their study, namely the seism of September 3, 1998 (see Table 2). Enescu et al. [1998] mentioned that probably these anomalous changes were not seen in all cases due to physical-mechanical events produced in areas where the earthquakes were in preparation, and due either to problems of the instruments or to some geomagnetic storms. The final conclusion of Enescu et al. [1998] was that it can be considered that in 92% of cases, these Vrancea earthquakes were preceded by magnetic anomalies (perturbations) that can be regarded as their short-term precursors. This percentage appears to be well above any realistic and reliable statistic.

As shown in columns 11-14 of Table 2, during most of the periods when anomalous precursory magnetic variations were mentioned, there were magnetic storms with $\Sigma Kp > 20$, due to solar effects or to periods with missing data. From the 19 classified precursory anomalies, five were a consequence of magnetic storms, and five were due to days of missing geomagnetic data. Only nine of these anomalies were found to be possible precursory anomalies, which thus decreases the probability of correlation of earthquake occurrence with geomagnetic anomalies from 92% to only 45%. This percentage relates to the strict case of the year 1998, under study here.

Figures 2-5 show the most interesting and representative examples of anomalous variations of the geomagnetic field, as presented in Table 2: (a) magnetic storms interpreted as

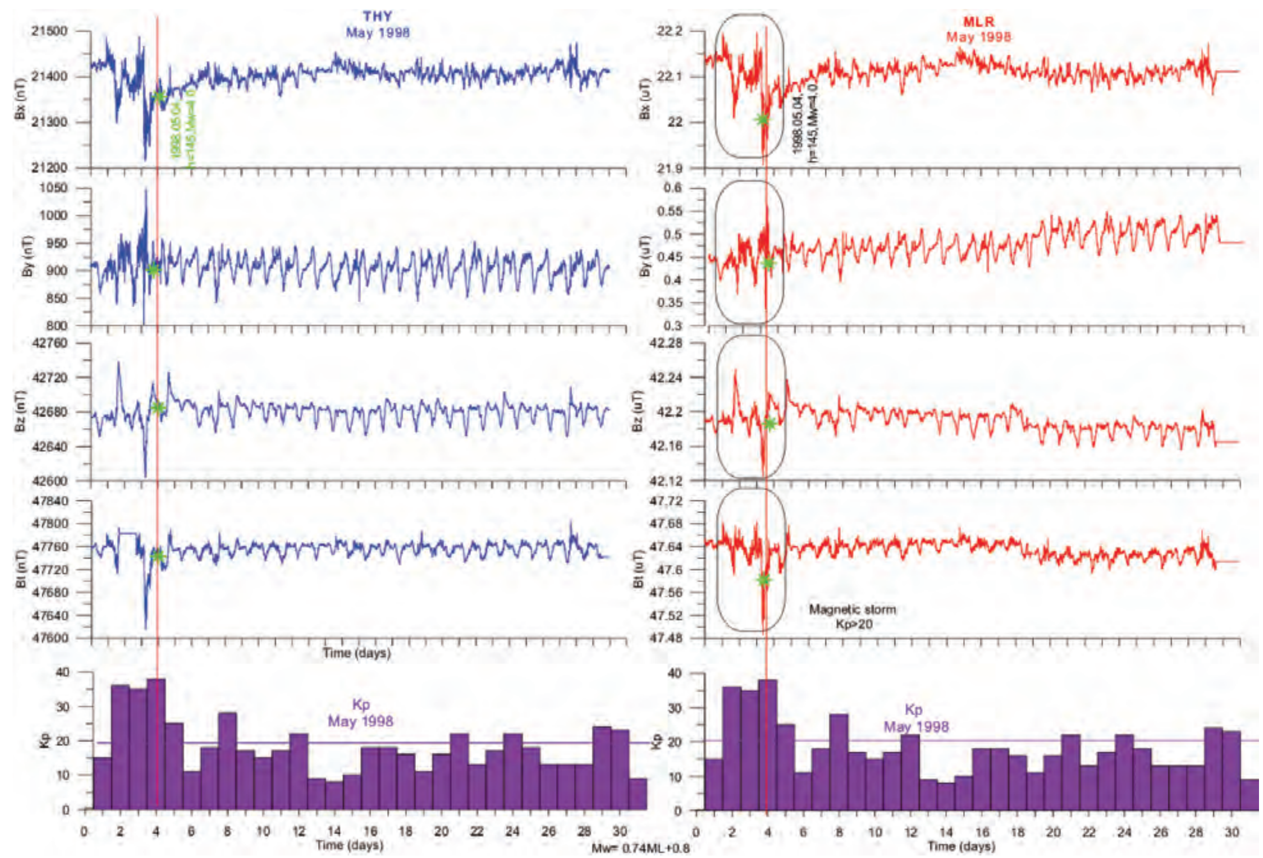


Figure 2. Solar storm that took place on May 2, 3, 4, 1998, had a triggering effect on the earthquake that occurred on May 4, 1998 *Mw* 4.0; h = 145 km). In this case, the geomagnetic anomaly was induced by the solar storm (as the *Kp* index reveals) and it is not a seismo-magnetic precursor.

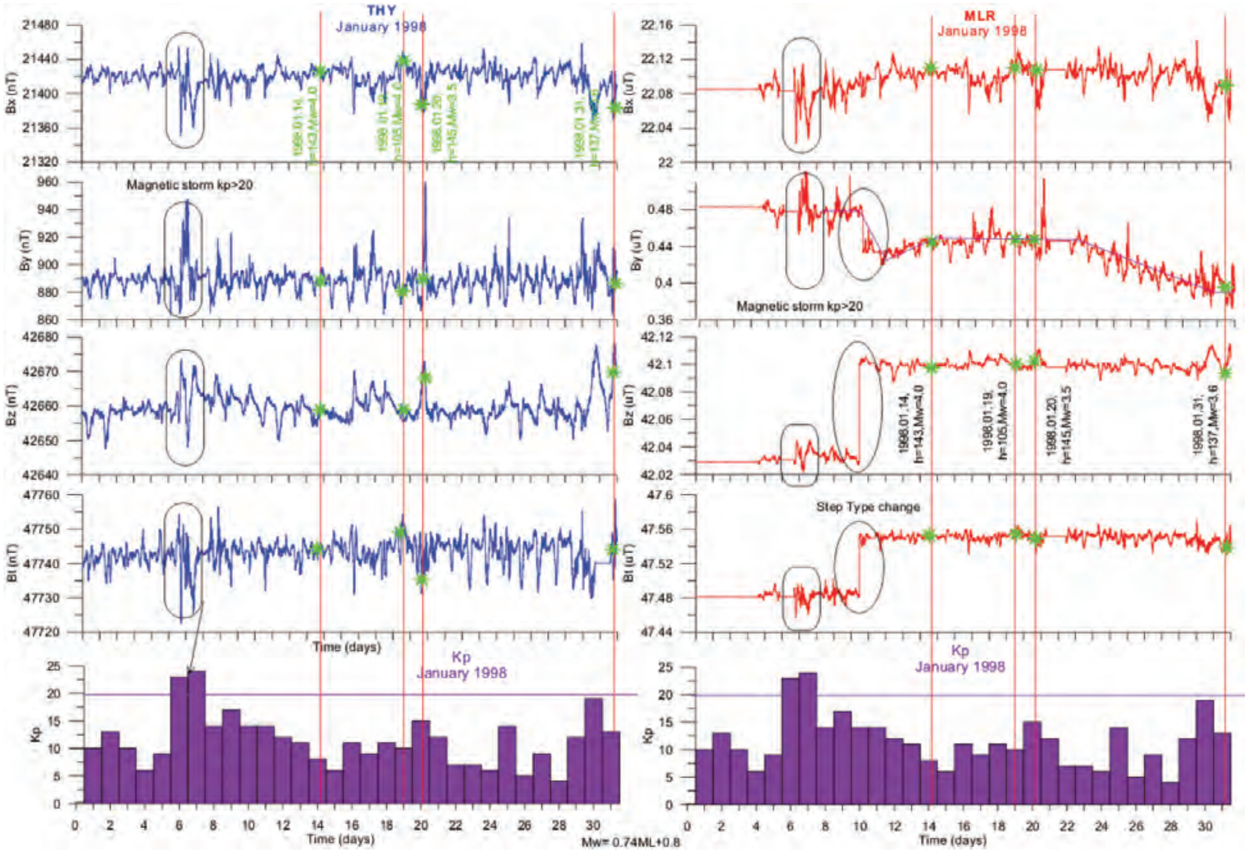


Figure 3. *Kp* indices of January 6, 7, 1998, reveal a magnetic storm. Two days later, on January 10, 1998, a step-change of Bz and By occurred. The By component developed a V-shaped anomaly with a duration of 4 days. An earthquake with magnitude *Mw* 4.0 (h = 143 km) occurred at the end of this anomaly.

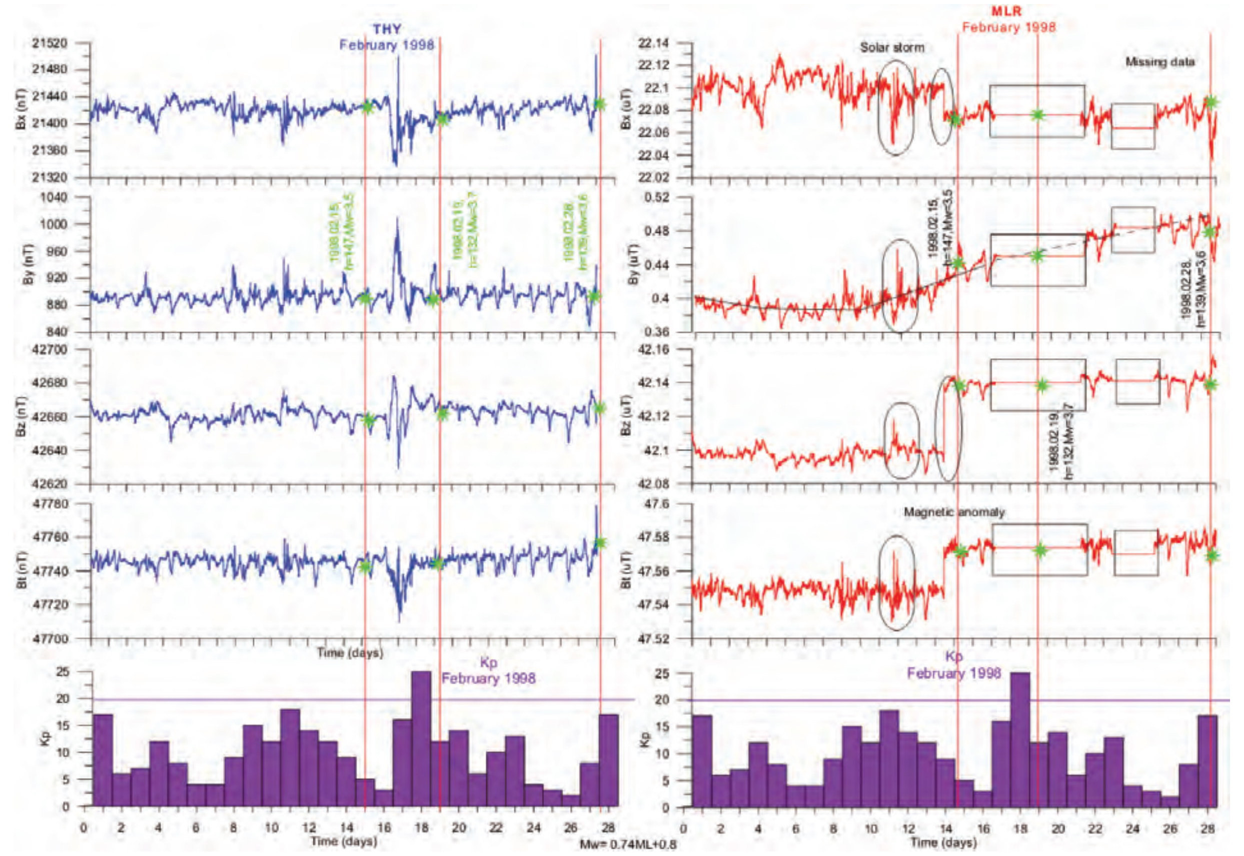


Figure 4. The V-shaped anomaly of By started on January 23, 1998 (see Figure 2), and continued until February 15, 1998, when the prior value of By was restored. One day before restoration, a step-change occurred on the Bx and Bz components. An earthquake with magnitude *Mw* = 3.5 (h = 147 km) occurred on February 15, 1998. Between February 17 to 21, 1998, there was a data gap. The same situation is seen for February 23 to 25, 1998.

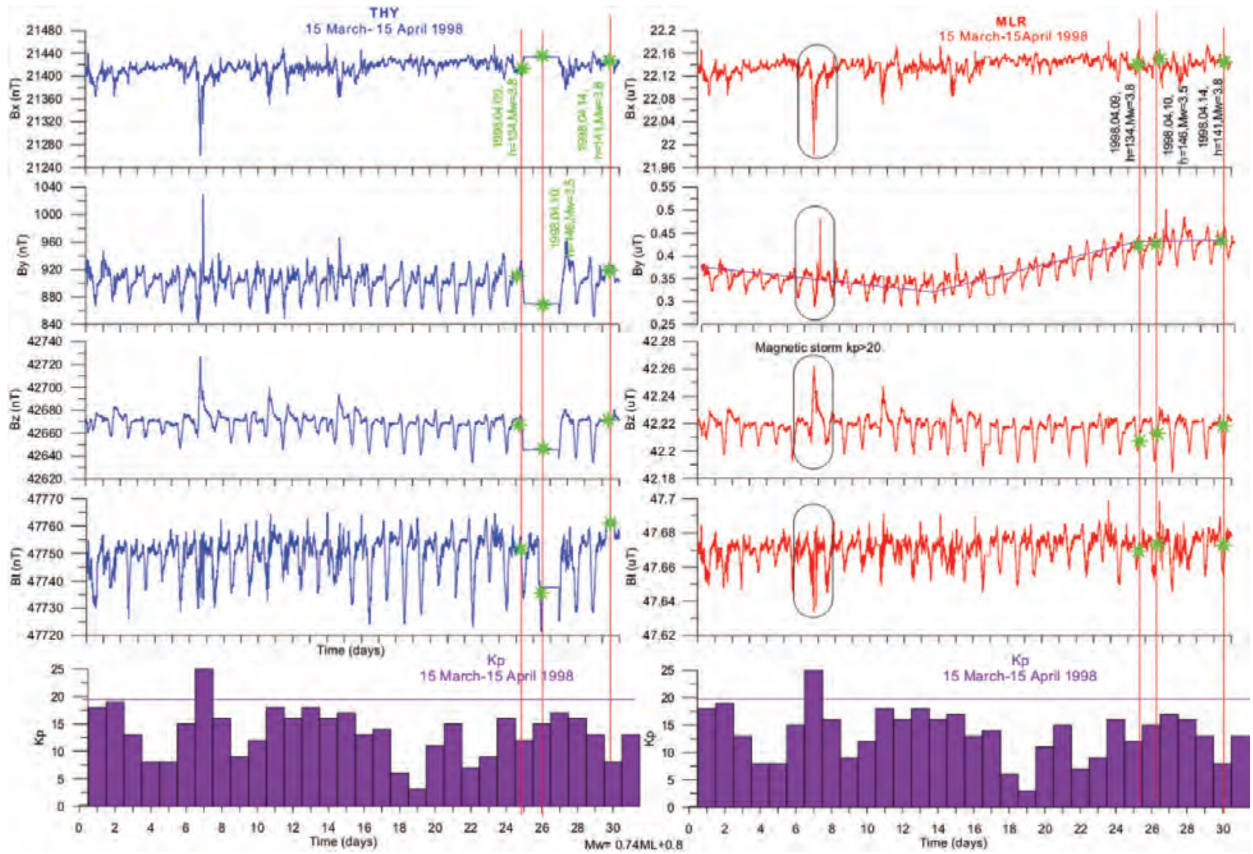


Figure 5. On March 21, 1998 (day 7) another magnetic storm (*Kp* = 25) induced a variation in the geomagnetic flux density. It can be seen that the By component has a V-shaped anomaly, which ends on day 25 (April 9, 1998). Two earthquakes (*Mw* = 3.8 h = 134 km, and *Mw* = 3.5 h = 146 km, respectively) occurred on April 9, 10, 1998.

seismo-magnetic anomalies, sometimes followed by earthquakes that might be triggered by the solar storms (Figures 2, 5); and (b) missing data that lead to misinterpretations caused by the stacking of non-consecutive data blocks (Figures 3, 4, data gaps) and seismo-magnetic anomalies (Figures 3, 4, 5).

Figures 2-5 illustrate the components of the magnetic field, for Bx, By, Bz and Bt, each for two stations: SUA or THY (left) and MLR (right). The time (in days) is given on the abscissa, and the values of each of these components (in nT for SUA and THY, and in μT for MLR) are given on the ordinate. X is positive pointing North and Y is positive pointing East. Figures 2-5 also show the times when the Vrancea earthquakes of magnitudes *Mw* >3.0 occurred during the period of this study. The *Mw* 3.0 moment magnitude was imposed as a threshold as significant disturbances cannot be detected before the Vrancea earthquakes of *Mw* <3.0.

(a) There were days, as for May 2, 3, 4, 1998, preceding the earthquake on May 4, 1998 (Table 2, line 14), when the solar storm reached more than half, ΣKp 36, 35, 38, respectively, of the maximum possible ΣKp of 72 (Figure 2). We consider that for the earthquake that occurred immediately after the end of the magnetic storm, the storm had a triggering effect, and there was no geomagnetic seismic precursor. The value of ΣKp was less than 15 for only two anomalous periods, which is the lower limit for a magnetic storm.

(b) Periods of missing data are visible in Figures 3 and 4, and these are explained in Table 2. Due to the missing data, in Figure 3 there is a misinterpretation of the date of the anomaly from January 9 that was actually on January 10, 1998. In Figure 4, the finish date of the V-shaped anomaly that started on January 23, 1998, cannot be specified exactly. From Table 2, it can also be seen that five of the stated anomalies were due to the missing data.

(c) The anomaly from January 9, 1998 (Table 2, lines 3, 4, 5) was considered by Enescu et al. [1998] as preceding three earthquakes: January 14, 1998 (*Mw* 4.0), January 19, 1998 (*Mw* 4.0) and January 31, 1998 (*Mw* 3.6). This anomaly was also classified in the present study as a seismo-magnetic precursory anomaly. From Figure 3, it can be seen that there was a magnetic storm with ΣKp >20 just two days before the magnetic anomaly, and there was also a day of missing data. The anomaly, indicated by Enescu et al. [1998] as a «a step-type change», appeared on the vertical component of the magnetic recordings. Also in Figure 3, another type of anomaly can be seen, on the horizontal By component, which we refer to as a «V-shaped anomaly». The V-shaped anomaly corresponds to the step-type change in the Bz component. Nowadays, after 15 years of magnetic recordings and analysis, we can state that after a step-type change or a V-shaped variation in the magnetic components, an earthquake occurs, although not all earthquakes are preceded by these changes.

On January 23, 1998, another By V-shaped anomaly started, and lasted until February 16, 1998. On February 14, the V-shaped anomaly was accompanied by a step-type change for two components: Bx and Bz. An earthquake of *Mw* 3.5 occurred immediately afterwards, on February 15, 1998 (Figure 4). Instead of these anomalies, in the analysis of Enescu et al. [1998], lines 6 and 7 from Table 2 show an anomaly recorded on February 18, 1998, when there were no recorded data.

In Figure 5, it can be seen that on March 21, 1998, there was a solar magnetic storm with $\Sigma Kp = 25$, followed by a relatively quiet month, from both the seismic and magnetic points of view. On April 2, 1998, the geomagnetic index reached the smallest value for the months ($\Sigma Kp = 3$), and on the magnetic records there is no visible anomaly, as was erroneously presented by Enescu et al. [1998] (see Table 2, lines 10, 11). However, on the horizontal EW component, there is a large amplitude By V-shaped anomaly of 150nT with a long evolution of approximately 20 days. Two earthquakes occurred at the end of this V-shaped anomaly.

The last two columns of Table 2 give all of the revised anomalies.

4. Data correlations

As the investigated period was 15 years (1996 to 2011), which covers more than a complete solar cycle (the 23rd and the first part of the 24th solar cycles), the solar-terrestrial perturbations fluctuated from very low values (in 1996 and 2009, at the beginning and end, respectively, of the 23rd solar cycle; Archibald 2009) to very high values (in 2000 to 2001; the maximum of the 23rd solar cycle; Archibald 2006). These provided the ideal medium to observe perfect cross-correlation of geomagnetic intensity with solar perturbations and earthquake occurrence.

In this section we provide the statistical correlations of geomagnetic anomalies recorded over the last 15 years at MLR Seismic Observatory (Romania) with the earthquake occurrences and the solar magnetic storms after the correction and reprocessing of the whole set of the magnetic data. To discriminate local – tectonic - and global – solar - phenomena, the geomagnetic data from MLR Observatory are correlated with the global solar phenomenon using the geomagnetic indices *Kp* and compared with the data recorded at the SUA (Romania) and THY (Hungary) geomagnetic reference stations, which are located outside the epicentral region. These recordings were provided by the INTERMAGNET Project (www.intermagnet.org).

The possible seismo-magnetic anomalies considered in this study are those presented in section 3, namely the «step-type change», the «V-shaped anomaly» and the «reverse V-shaped anomaly». The step-type change anomaly has a very short period, while the two V-shaped anomalies are long period, minimum and maximum, respectively, anomalies. In future we will look for other types of anomalies with spectral evidence and using different data processing techniques, like the terminator time deviation from the sunset or sunrise hours.

During our studies, we considered different causes for the recording of such anomalies, like equipment problems, temperature problems, or displacement of magnetic objects in the vicinity of magnetometers. One after another, these causes were eliminated by isolating the equipment from man-made magnetic influences and by installing a Weather Stations WS-3600 type with temperature, pressure and humidity continuous monitoring.

As MLR Observatory is situated near to the Carpathian electrical conductivity anomaly (CECA), the long period anomalies (V-shaped and reverse V-shaped) might be linked to electrical conductivity variations along the CECA, which forms not only a tectonic boundary, but which also represents a peculiar conducting channel, as an 'open gate' to the intermediate depth seismically active Vrancea zone [Stanica et al. 2006; Stanica and Stanica 2007]. The same type of long-period magnetic anomaly was also reported by Takla et al. [2011] prior to two crustal *Mw* 5.7 earthquakes that occurred in Italy in the Molise region on October 31 and November 1, 2002.

Figures 6 and 7 show examples of the graphs used for the statistical correlations. The graphs refer to the magnetic intensity Bx, By and Bz components, and to the total magnetic field intensity Bt, for two stations: SUA/THY (left panel) and MLR (right panel), and to the daily sums of the geomagnetic index *Kp* (ΣKp). The graphs shown in Figures 6 and 7 were chosen as representative examples of a V-shaped long-period magnetic anomaly recorded on the horizontal component by the MLR Observatory data prior to the *Mw* 4.4 (October 2, 2008, 14:04:48.2, h = 148 km) intermediate Vrancea earthquake. The anomaly started on September 16, 2008, immediately after a minor magnetic storm, and ended on October 6, 2008, with an earthquake of *Mw* 3.5. The *Mw* 4.4 earthquake was just at the minimum point of the anomaly. The data from the MLR Observatory are also compared with the data recorded at SUA, and are correlated with the seismicity and the solar activity.

Studying the monthly data year after year from 1996 until now, all the magnetic anomalies were tabulated and they were correlated with possible causes as the earthquake preparation stages, missing data or solar storms. Table 3 provides a part of this analysis as an example, as it is not possible to present a

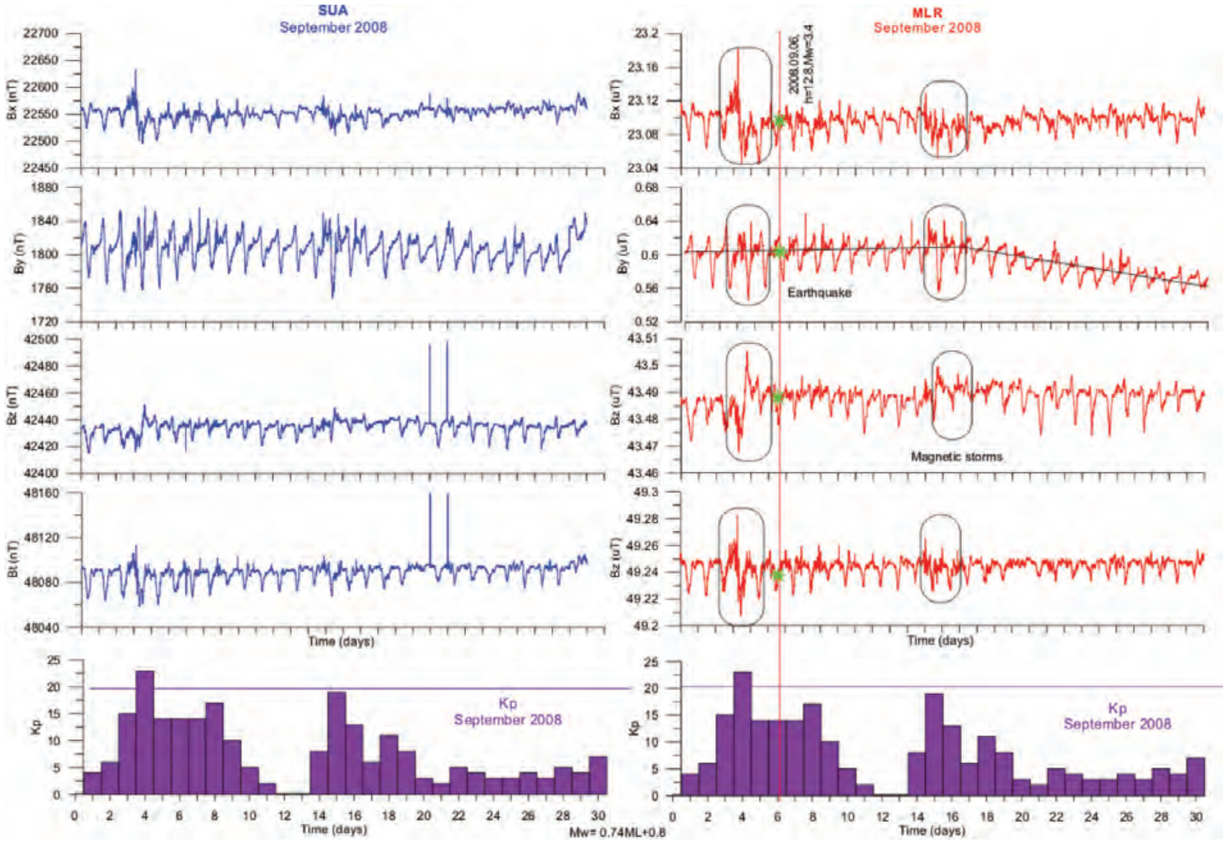


Figure 6. The V-shaped anomaly recorded on the horizontal component By of the MLR Observatory data prior to the $Mw = 4.4$ (October 2, 2008) crustal Vrancea earthquake.

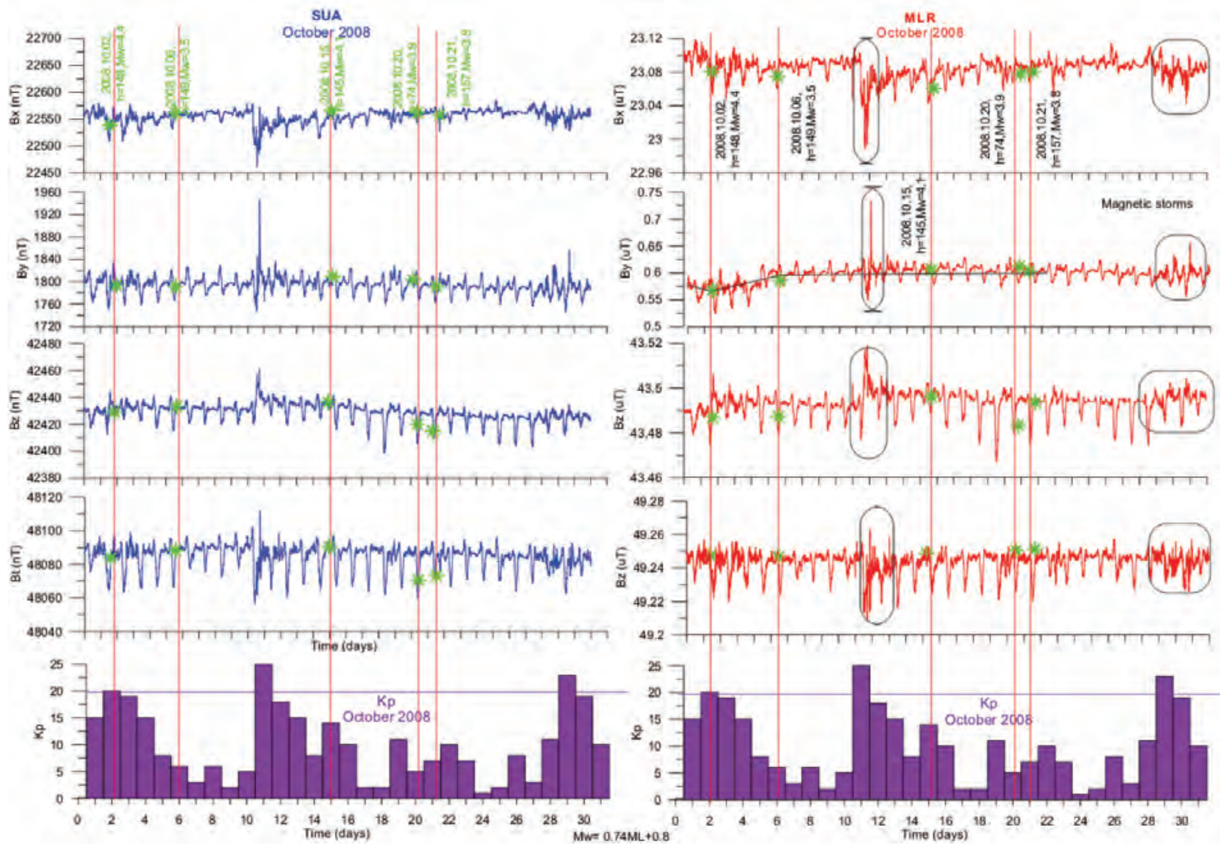


Figure 7. The V-shaped anomaly recorded on the horizontal component By of the MLR Observatory data prior to the $Mw = 4.4$ (October 2, 2008) crustal Vrancea earthquake.

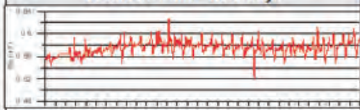
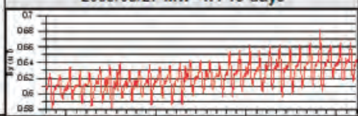
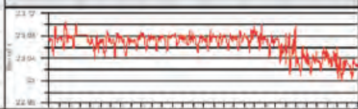
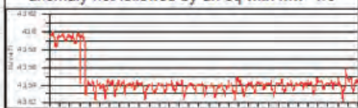
Date of anomaly occurrence	Anomaly duration in days	Anomaly type and amplitude	Maximum occurred earthquake in a time interval of 20 days	Earthquakes list (Romplus M>3)	No of days	Lat	Long	Depths	Mw	Obs.
2009/03/13	19	v/y	2009/03/21 Mw=4.0 8 days	2009/03/13 14:10:43.8	1	45.45	26.48	152.6	3	
		10nT		2009/03/14 20:46:01.9	1836	45.38	26.48	136.9	3	
				2009/03/15 11:07:55.9	2698	45.45	26.38	144.4	3	
				2009/03/15 18:42:23.2	3152	45.56	26.6	125.9	3	
				2009/03/15 19:37:47.6	3207	45.25	27.22	11.3	3.1	
				2009/03/17 10:47:52.1	5557	45.59	26.39	155.2	3.2	
				2009/03/18 22:20:41.5	7690	45.61	26.56	135.7	3.4	
			eq preceeded by an anomaly	**2009/03/21 22:08:56.6**	**11998**	**45.35**	**26.24**	**142.6**	**4**	**8**
				2009/03/23 17:19:44.2	14589	45.44	26.26	132.8	3.2	
				2009/03/25 02:44:39.6	16594	45.55	26.32	152.4	3.1	
				2009/03/27 21:04:23.0	20574	45.56	26.44	128.5	3	
				2009/04/01 00:51:22.2	26561	45.57	26.44	129.2	3	
				2009/04/02 14:02:31.4	28792	45.67	26.46	150.7	3.4	
				2009/04/03 03:47:42.2	29617	45.42	26.26	129.7	3.2	
				2009/04/07 19:00:21.2	36290	45.6	26.55	141.9	3	
				2009/04/08 04:38:41.6	36868	45.67	26.61	146.3	3.2	
			eq without anomaly	**2009/04/12 16:51:38.6**	**43361**	**45.7**	**26.58**	**143.7**	**4.1**	**30**
				2009/04/15 10:37:53.4	47307	45.67	26.43	156.9	3.2	
				2009/04/15 18:04:42.5	47754	45.46	26.34	128.5	3.2	
				2009/04/16 17:44:06.2	49173	45.57	26.6	118.5	3	
23/04/2009	2	missing data		2009/04/23 11:56:18.2	58905	45.59	26.35	153.6	3.4	
			eq without anomaly	**2009/04/25 17:18:48.0**	**62107**	**45.68**	**26.61**	**109.6**	**5**	**43**
			might an anomaly occured during	2009/04/26 23:19:15.9	63907	45.69	26.64	103.6	3.8	
			the days with missing data?	2009/04/28 05:19:15.9	65707	45.86	26.94	66.7	3.4	
				2009/05/01 14:04:51.3	70553	45.53	26.47	128.4	3.5	
				2009/05/09 09:00:29.9	81769	45.49	26.27	124.7	3.4	
2009/05/12	14	Ip increase y	2009/05/12 Mw=4.4 0 days	**2009/05/12 01:15:12.1**	**1**	**45.55**	**26.39**	**134.5**	**4.4**	**0**
		30nT/month	2009/05/27 Mw=4.4 15 days	2009/05/16 22:58:41.0	7064	45.75	26.56	143.8	3.2	
				2009/05/19 13:20:39.0	10806	45.69	26.52	157.9	3	
				2009/05/27 03:12:50.5	**21718**	**45.69**	**26.49**	**151.9**	**4.4**	**15**
				2009/05/29 00:30:52.2	24436	45.76	26.67	130.8	3.5	
				2009/06/03 10:26:59.9	32232	45.71	26.68	77.6	3.2	
2009/06/20 2009/06/23	6 1	decrease/x (40nT) s/y and z	2009/06/27 Mw=4.0 7 days	2009/06/20 10:26:59.9	1	0	0	0	0	
2009/06/24	1	kp>20		**2009/06/27 02:01:24.3**	**9575**	**45.8**	**26.75**	**89.7**	**4**	**7**
				2009/07/08 16:31:20.7	26285	45.81	26.74	72.5	3.5	
				2009/07/15 12:07:43.2	36101	45.64	26.47	147.2	3.7	
2009/07/22	1	kp>20		**2009/07/24 20:27:09.7**	**49560**	**45.7**	**26.61**	**140.2**	**4.6**	**34**
				2009/07/25 05:57:42.1	50131	45.49	26.32	133.1	3.8	
				2009/07/27 10:23:44.4	53277	45.45	26.25	126.3	3.5	
2009/08/04	1	s/y and z	2009/08/17 Mw=3.5 13 days	2009/08/04 04:39:29.9	1	0	0	0	0	
		100nT	anomaly not followed by an eq with Mw>4.0	2009/08/08 04:39:29.9	5761	45.84	26.72	120.9	3.1	
				2009/08/12 02:32:20.9	11394	45.57	26.45	150	3.2	
				2009/08/13 20:29:09.4	13911	45.66	26.47	114.2	3	
				2009/08/15 10:31:31.5	16193	45.73	26.59	98.2	3.3	
				2009/08/17 14:39:39.8	**19321**	**45.74**	**26.58**	**152.5**	**3.5**	**13**
				2009/08/18 18:45:51.3	21007	45.17	26.47	106.3	3.1	
				2009/08/18 20:00:19.5	21081	45.59	26.47	126.2	3.2	
				2009/08/22 20:57:16.9	26898	45.37	26.42	100	3	
				2009/08/27 14:25:27.5	33706	45.6	26.45	130.9	3.8	23
				2009/08/27 23:31:33.5	34252	45.75	26.55	164.6	3.5	24
				2009/08/31 10:07:28.3	39208	45.56	26.2	120.7	3.2	

Table 3. Example of cross correlation table between earthquakes with *Mw* >3.0, magnetic anomalies, and solar magnetic storms with *Kp* >20.

Table here containing more than 10,000 lines. Thus, Table 3 contains the earthquake catalog for *Mw* >3.0, the dates when magnetic anomalies occurred, their durations in days, the shapes and the amplitudes of the anomalies, and the days when solar magnetic storms hit the Earth (Σ*Kp* >20). All of this information was cross-correlated to investigate any statistical relationships among these different phenomena.

Only 12 years of recordings were synthesized for this correlation study, because during the first two years of the magnetic records there was inconsistent data, and the earthquake catalog for 2011 has not yet been completed.

From these studies, we can conclude that:

1. From the 3,022 earthquakes with *Mw* >2.0 recorded over these 12 years, 1,180 earthquakes had *Mw* >3.0 (39%) and were used for the correlation studies. From the 1,180 tabulated earthquakes, 403 had *Mw* >3.5 (34%), 121 had *Mw* >4 (10%), 19 had *Mw* >4.5 (<2%) and only 4 had *Mw* >5(<0.5%). From the 121 earthquakes with *Mw* >4, 57

earthquakes (47%) were preceded by visible magnetic anomalies, and 53 (43%) were not, and 11 of these earthquakes (9%) were inside the missing periods of the magnetic recordings. If we exclude these last 11 earthquakes, then 52% of earthquakes with *Mw* 4.0 were preceded by seismo-magnetic precursors and 48% were not.

2. From the 66 magnetic anomalies, 42 (64%) were followed by an earthquake with *Mw* >4.0 and 24 (36%) by an earthquake with 3.5 <*Mw* <4.0, in a time interval of 20 days, i.e. all of the magnetic anomalies (100%) were followed by earthquakes with *Mw* >3.5;

3. All of the the solar storms with *Kp* >20 produced perturbations of the geomagnetic field, with different amplitudes and frequencies, although to date there is no clear evidence that the geomagnetic storms are triggering earthquakes. Further studies are needed to arrive at a reliable conclusion regarding this correlation.

4.1. The largest intermediate depth Vrancea seismic event from the past 15 years

In this section, the largest intermediate depth earthquake that occurred during the study period is analyzed, along with its corresponding geomagnetic anomalies.

Figure 8 shows the V-shaped long-period anomaly that was recorded on the horizontal component By of the MLR Observatory data prior to the *Mw* 6.0 (October 27, 2004, 20:34:36.4, h = 98.6 km) intermediate depth Vrancea earthquake. These data from the MLR Observatory are compared with the data recorded at SUA and correlated with the seismicity and the solar activity. Starting from October 10, 2004, the eastern component of the local geomagnetic field recorded at the MLR Observatory deviated from the general pattern (recorded by the other observatories) and started to decrease «on its own». The issue is that after showing a relative steep decay, it reached a lower peak of about –40nT, which is far greater than the expected values of an anomaly that would appear at a hypocentral distance of about 122 km. After this, the value of the eastern component started to increase slowly, following a specific slope, towards a normal mean value. The earthquake occurred when the value of this component was «restored» to its mean value. It should also be noted that two days after the anomaly started (on October 12, 2004), the *Kp* index shows higher values, which denote solar storms, and these are easily visible on the recordings.

This example gives us the hope that future large earthquakes will be preceded by such minimum-type or maximum-type, long-period, magnetic anomalies, which would provide the possibility of forecasting the occurrence of extreme seismic events.

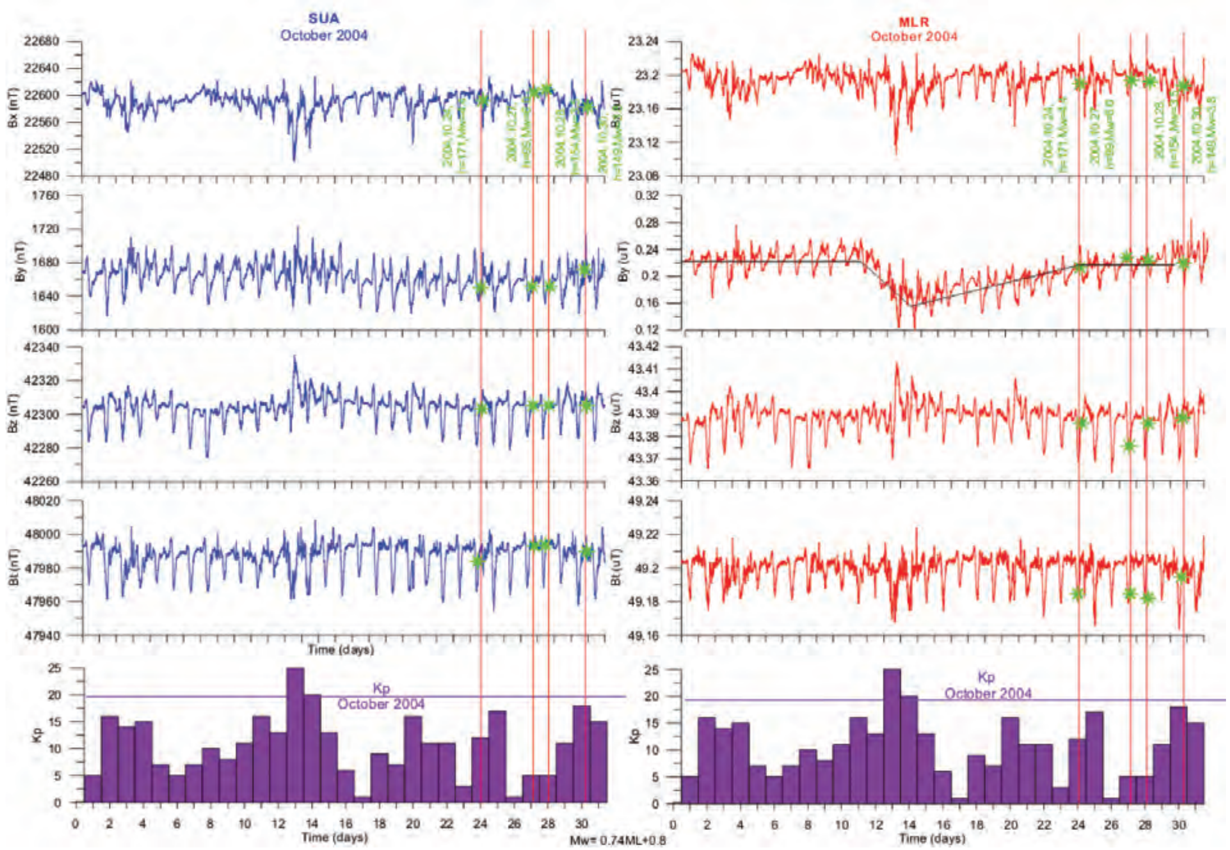


Figure 8. The V-shaped anomaly recorded on the horizontal component By of the MLR Observatory data prior to the *Mw* = 6.3 (October 27, 2004) intermediate depth Vrancea earthquake.

5. Conclusions

The main purpose of the present study was to evaluate the data obtained after 15 years of geomagnetic surveillance, to obtain more robust conclusions on the nature of various irregularities in the geomagnetic field variations. The present study reveals some issues regarding the interpretation of the geomagnetic activity within the Vrancea seismic zone prior to earthquakes with *Mw* >3.0 [Enescu et al. 1998, 1999a,b, 2001]. Some geomagnetic anomalies identified and presented as precursory signals are seen to be induced either by increased solar activity (as the *Kp* index demonstrates) or by dysfunction of the data acquisition system, which produced inconsistent data with numerous gaps. The first part of our study demonstrates that the previously reported precursory anomalies were insufficiently investigated, which led to some regrettable misinterpretations. In our opinion, more careful approaches in the future will be beneficial for these kinds of studies.

The whole geomagnetic dataset recorded at the MLR Observatory from 1996 to the present was re-evaluated and tabulated. Geomagnetic data recorded at other observatories, such as SUA and THY, were also studied, to identify the global anomalies and to correlate these with the solar activity.

After evaluation of the examined period of 15 years, the following observations were made:

1.Two kinds of anomalies are noted: the step-change anomaly (short period), and the By V-shaped anomaly (long period). The step-change anomalies are seen as modifications of the amplitude of the Bt vector, while the V-shaped anomalies are seen as changes in the orientations of the components of the Bt vector.

2. Most of the anomalies were followed by an earthquake with *Mw* >4.0 in a time interval of less than 20 days, although not all earthquakes were preceded by these kinds of anomalies.

3. There is no visible connection between the amplitude of these anomalies, their duration or the precursory time and the magnitude of the earthquakes that occurred afterwards.

4. There is no clear evidence that geomagnetic storms have an earthquake-triggering effect.

Data and sharing resources

– Geomagnetic field records from Surlari and Tihany INTERMAGNET Observatories http://ottawa.intermagnet.org/apps/dl_data_def_e.php;

– Seismic data for the Vrancea source zone, taken from the seismic bulletins of the National Institute for Earth Physics - http://www.infp.ro/ro/lista_evenimente/local;

– Daily geomagnetic index *Kp* from the NOAA/ Space Weather Prediction Center -http://www.swpc.noaa.gov/ftpdir/indices/DGD.txt.

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